ICE-RIFT SEISMICITY IN ANTARCTICA: AN ANALOG FOR UNDERSTANDING TIDALLY GENERATED SEISMIC ACTIVITY ON ENCELADUS AND EUROPA. K. G. Olsen[1,2], T. A. Hurford[1], N. C. Schmerr[3], K. M. Brunt[1,3], [1]NASA Goddard Space Flight Center, Greenbelt, MD (kira.olsen@nasa.gov), [2]Howard University, Washington DC, [3]University of Maryland, College Park, MD.

Introduction: The icy crustal shells of Enceladus and Europa are relatively young and exhibit abundant rifts, ridges, and offset lineaments, most of which are thought to be formed by tidal processes [1]. Brittle deformation within ice, such as fracturing and slip events, will generate seismic waves that contain information about the orientation and magnitude of stress within the ice, depth of fracture, and will be key sources of energy for passive sounding of the interiors of these bodies [2, 3]. Future lander missions to icy moons (including the Dragonfly mission to Titan) are slated to include seismometers, which will allow for analysis of seismicity generated by lunar-ice deformation. These new datasets will rapidly advance our understanding of the origins of these surface features as well as the thickness of icy shells and interior structure [4].

In preparation for seismometer deployment on icy worlds, a thorough understanding of the character of similar ice-generated seismicity on Earth is needed. Terrestrial analog work will inform seismometer site selection for future missions, help to define instrument requirements, and provide test data for best developing on-board processing algorithms and rapid data analyses. The polar ice shelves on Earth are perhaps the best terrestrial analogs to the ice shells of Enceladus and Europa. The Ross Ice Shelf in West Antarctica is a particularly apt analog as this rigid ice shelf undergoes daily deformation in response to ocean tides. This ice shelf is also unique in that it contains multiple rifts within the interior of the ice sheet, similar to features imaged on icy-ocean world surfaces. Study of seismicity associated with these interior features will advance our understanding of how tidal action affects deformation within ice rifts, and of the stress state within the ice at different tidal phases. In addition, this work will help clarify how seismometer location (distance and azimuth) relative to a rift affects observational capabilities of both local (rift-generated) and distant (teleseismic) seismic events.

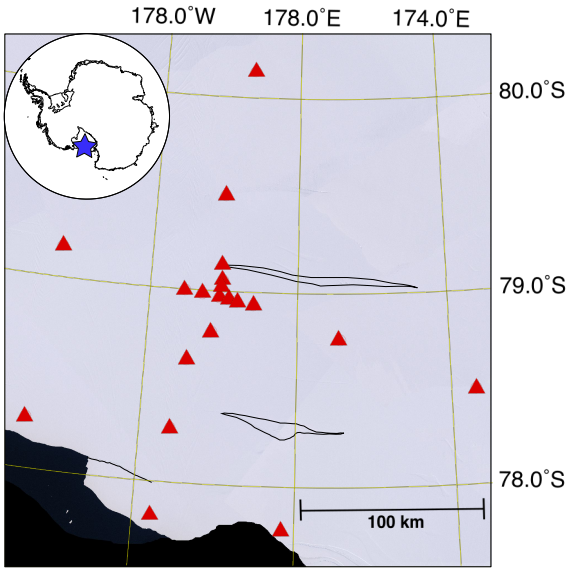

Figure 1. Map of study area on the Ross Ice Shelf, Antarctica, showing ice shelf (grey), ocean (black), ice-shelf rifts (outlined in black), and seismic stations (red triangles). Background image: Landsat-7 image mosaic. Inset: Map of Antarctica showing location of Ross Ice Shelf (blue star).

Analysis of Ice-Rift Seismicity: We investigate seismic events surrounding two rifts within the Ross Ice Shelf using 28 on-ice seismometers that collected data on the Ross Ice Shelf from 2014 through 2016. These broadband seismic stations are located at a range of distances and azimuths from the rifts (Figure 1), which allows for investigation into optimal source-to-station spacing, analysis of radiation patterns, and study of attenuation within the ice.

We detect seismic events using an automated short-term average/long-term average approach, coupled with manual detection review. For this study, we distinguish between ice-generated local events and teleseismic tectonic events using event locations and timing referenced against a global catalog of tectonic events [5, 6]. Future work will attempt to distinguish such events without a global catalog. To locate events, we use surface-wave polarization analysis to constrain the source azimuth of on-ice events, and explore a range of different methods to estimate source-to-receiver distance. Using our new catalog of ice-generated events, we analyze event timing, spectral content, and relationship to ocean tides.

The majority of seismic stations within 30 km of the ice-shelf rifts record multiple seismic events per day. As expected, higher numbers of seismic events are detected by the seismic stations located closest to the rifts, and the number of detections fall off with increasing source-to-station distance. The ice-generated events we identify contain significant high-frequency energy in the period band 5 – 20 Hz, consistent with ice-fracture events recorded in other locations [7].

Discussion and Conclusions: Our preliminary results demonstrate that seismic stations located within 5 km of interior ice-shelf rifts detect seismic events throughout the entirety of the tidal cycle (Figure 2). Regions of the ice shelf that experience similar tidal influence but are far (>100 km) from any interior rifts record very low levels of seismicity, indicating that the majority of seismogenic ice-shelf deformation occurs along large, existing rifts. Future analysis of the stress state within the ice, inferred from the focal mechanisms of individual seismic events, will provide additional details of the relationship between tidal flexure and rift motion.

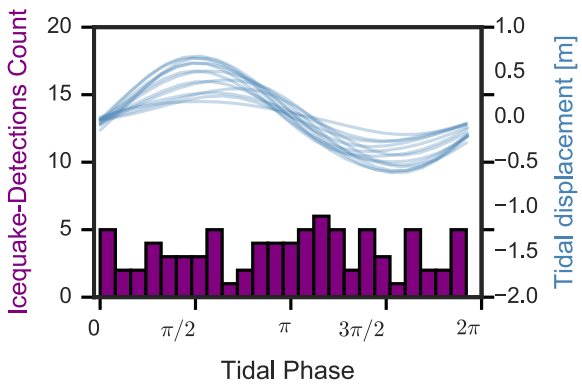

Figure 2. Number of icequakes (purple bars) detected as a function of tidal phase. Icequakes shown are those detected by a seismometer located 3 km from an ice-shelf rift over a period of two weeks. Daily vertical tidal-displacement values (blue lines) were calculated using the TPX09 tidal model [8] at the seismometer location.

The ideal seismometer-deployment location for future icy-moon landers will allow observation of both small-amplitude, local seismic events as well as larger-amplitude seismic events occurring elsewhere on an icy-ocean world surface. The model for seismicity driven by tidal-energy dissipation on planetary bodies presented by Hurford et al., 2020 [9] predicts routine generation of seismic events up to M_W 5.3 on Europa. We demonstrate that a seismometer located 3 km from a Ross Ice Shelf rift can detect surface-wave arrivals from tectonic earthquakes of approximately this magnitude (M_W 5.5) located up to ~2500 km away (equivalent to a 90° source-to-station offset on Europa). Spectral differences between these teleseismic events and the more common rift-generated seismicity make it possible to distinguish between the two types of events using a single seismic station (Figure 3). This suggests that a future icy-worlds lander could deploy a seismometer within ~5 km of a rift and successfully record and distinguish between expected local and global seismicity.

Preliminary results suggest that source-to-station distance has a larger influence on successful event detection than does any azimuthal variation in station location relative to a rift tip. Analysis of this seismic dataset helps clarify the ability of an on-ice instrument to record low-magnitude seismic events generated at a range of distances, and helps to inform future seismic study of icy worlds. Detection of tidal modulation of seismicity will require a catalog of completeness that includes seismic events at the small-magnitude end of the Gutenberg-Richter relationship. Planned future work involving a targeted deployment of seismic stations within ~5 km of a rift will capture these events and help investigate further details of tidal influence on rift seismicity.

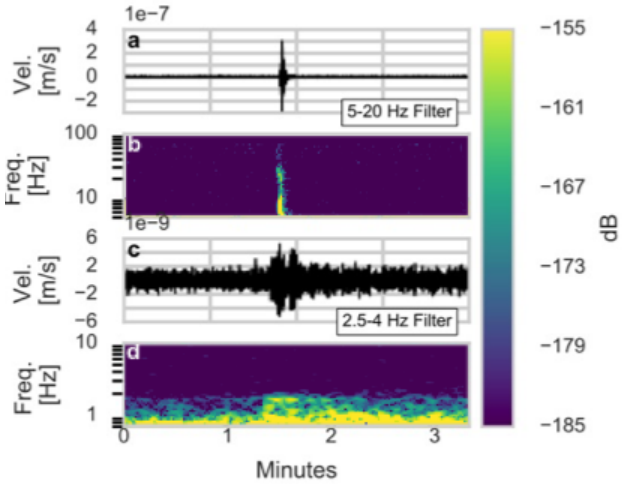

Figure 3. Differences between seismograms and spectrograms from a local icequake (3 km away; a and b) and a teleseismic earthquake (~2500 km away; c and d) recorded at the same station. Color scales are the same for subplots b and d, but y-axes differ.

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